FOAMED HYDROCARBONS: AN EFFECTIVE AND ECONOMICAL ALTERNATIVE TO CONVENTIONAL STIMULATION METHODS

MICHAEL A. SMITH AND DAVID L. HOLCOMB
Cardinal Chemical, Inc.

ABSTRACT

Foamed hydrocarbons have been applied with great success in paraffin and heavy hydrocarbon penetration, foamed fracturing treatments, and fluid cleanout in wells in which hydrostatic pressure interferes with or completely stops gas production. Results of lab and field tests show this system to be effective as well as economical as an alternative in well treatment.

The paraffin and heavy hydrocarbons removed in foamed aromatic hydrocarbons constituted up to 41 percent of the total volume of solids removed after a 1 hour shut-in period.

A nonproductive well in the San Miguel formation which had been shut-in for a year was fractured with foamed gel condensate resulting in 70 MCF gas/day. A fracturing system designed with foamed gelled kerosene used to fracture the Crockett Sand Formation produced a 105 BOPD and 130 MCF/day well where previous gelled kerosene fracturing treatments yielded 12 to 30 BOPD and no gas. After 30 days, the well still made 70 BOPD and 100 MCF/day.

Gas wells in the Sonora area have periodical condensate buildups which restrict the gas flow. With the addition of a hydrocarbon foamer, the hydrostatic head was removed in the form of foamed condensate, allowing production of the natural gas.

Procedures and results of lab and field tests will be discussed along with comparative results of more conventional treatments.

INTRODUCTION

Practical uses for foams have been well documented in oil field treatments.[1,5] Until recent years foams have been restricted to aqueous fluids, acids, and alcohols as the liquid phase. Combinations of water and methanol were used in foam fracturing to take advantage of the beneficial properties of alcohol. The primary advantages of hydrocarbon-based stimulation fluids are rapid clean-up of the well, compatibility with well fluids, and reduction of formation damage due to clay swelling. Conventional uses of these foamed systems have been modified to include hydrocarbon fluids as the liquid phase.

In past treatments using conventional methods (whether aqueous or hydrocarbon based), friction reduction additives, fluid loss additives, gels, and other chemical additives had to be used to achieve the natural properties of foams. These properties, as listed by Blauer and Kohlahaas for fracturing fluids, are high sand-carrying and sand-suspending capability, low fluid loss, low hydrostatic head, low pressure drop due to friction, quick recovery, low formation damage, and no reduction of fracture conductivity due to insoluble fines.[1] The ability to foam hydrocarbons now allows the combination of desirable properties for both the hydrocarbons, as listed above, and foams.

FOAM RHEOLOGY

The rheology of foams, as applied to well treatment, both acidizing and fracturing, has been researched to a great extent. Foams demonstrate the properties of a Bingham plastic fluid in laminar flow.[1,5,6,7] The shear-stress to shear-rate relationship of foams at shear rates greater than 10,000 sec^{-1} is linear at any foam quality as shown by Mitchell. Shear-rates below 20,000 sec^{-1} can be linearized by subtracting the apparent yield strength. Figures 1 and 2 show Mitchell's Bingham plastic viscosity and yield stress of foam. Figure 3 shows the relationship of effective viscosity as derived by Holcomb and Blauer.

Fluid loss characteristics and fracture fluid coefficients show the added advantages of foam as a fracture fluid.[1] The low values make this system an

BINGHAM PLASTIC VISCOSITY OF FOAM

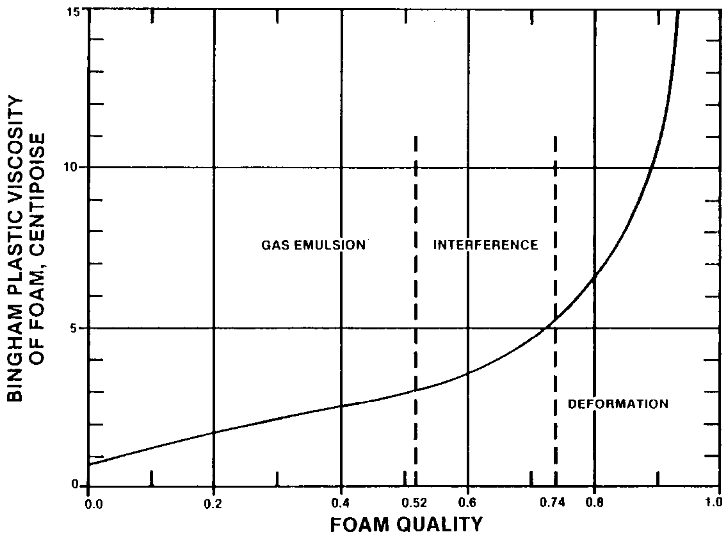


FIGURE 1

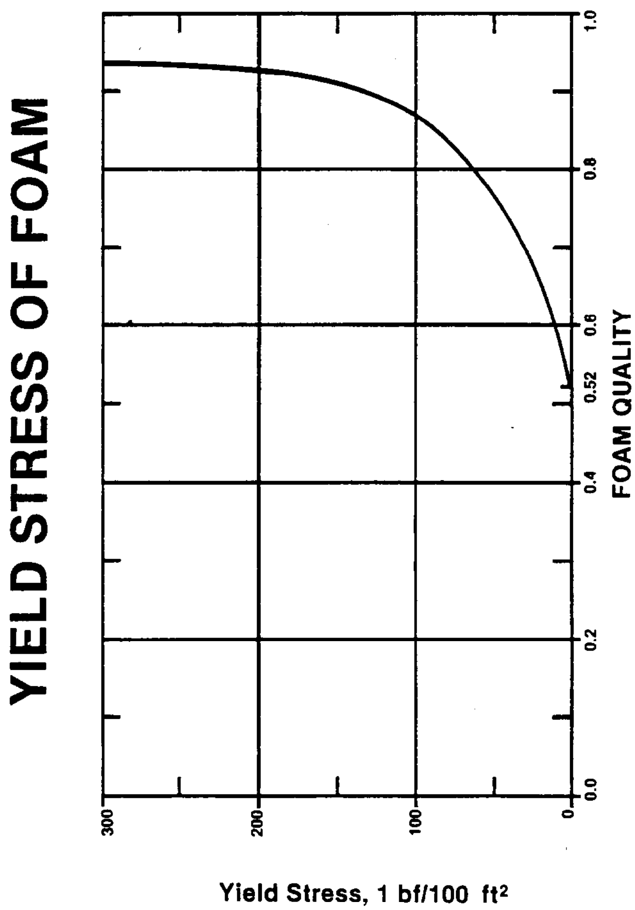


FIGURE 2

EFFECTIVE VISCOSITY OF FOAM

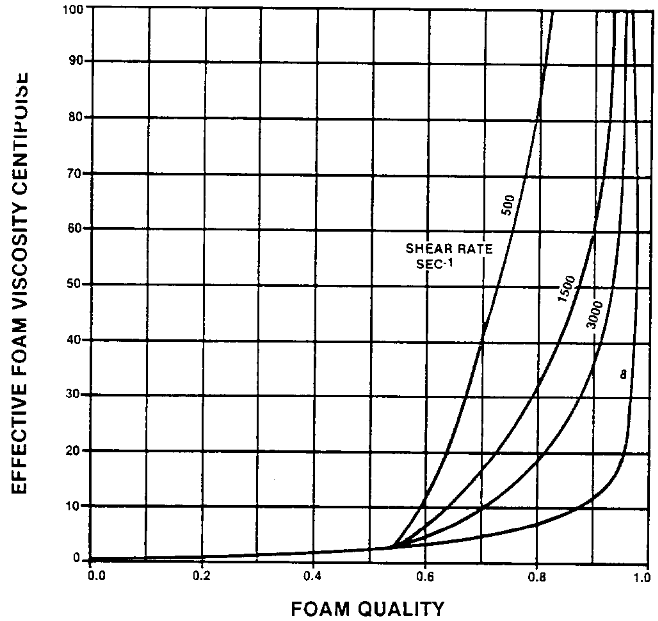


FIGURE 3

improvement over there using as gels and emulsions as fracturing fluids.

Sand-suspending capability of foam is much greater than that of water or gelled water.[1] Because of this, improved placement of proppant is achieved. Static foam, as in a fracture, can suspend sand for an extended period of time. Additional advantages are listed by Blauer and Kohlhaas.

FOAMED HYDROCARBON APPLICATION

Hydrocarbons that have been foamed in the field are condensate, kerosene, and xylene. These foams have been used in fracturing fluids, clean-out fluids and load build-up recovery. The use of foamed hydrocarbons allows rapid treatment and reduces non-productive time for these wells. These treatments have been successfully field tested on both oil and gas wells.

In fracturing with foamed hydrocarbons the gelled liquid phase is passed through a blender where the proppant can be added at a regulated rate. The foaming agent should be added at this point or downstream to avoid surface foaming by agitation. If the base hydrocarbon is gelled, the foamer is designed to begin breaking the gel on the fly before the foam is generated. This allows the foamed hydrocarbon to be the primary proppant carrier, and it allows for faster clean-up as well because it is not necessary to wait for the gelled portion of the system to break. Because of the nature of foam fracturing where a higher concentration of proppant must be carried by the liquid phase (one-third to one-fifth the normal volume of fluid), special mechanical equipment or a clean gel system should be used to ensure the suspension of the proppant. Mechanical adjustments consist of additional agitation devices in the blender tub and a return manifold to circulate exchange fluids being discharged by the blender through the pump and back to the blender tub. By the use of this mechanical method of concentrating the proppant suspending fluids, it is possible to pump a proppant slurry to the point where foaming takes place. The gas, normally nitrogen, is added to the fluid at a "Y" in the line downstream from the pumps. The turbulence of the fluid, in this case hydrocarbon, combined with the turbulence of the addition of the gas phase acts as a foam generator. The foam is then injected into the well. See Figure 4 for foam job set-up.

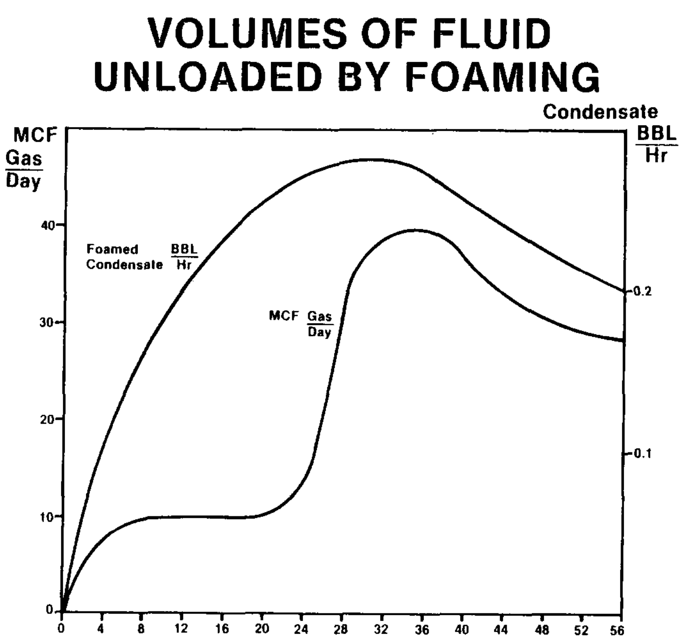


FIGURE 4

The foam quality of the fracturing fluids has been regulated by a rate meter, placed before the gas phase is injected, to determine the liquid rate by metering the rate of the gas phase before its injection. The quality can then be easily calculated as it is the ratio of gas volume (Vg), to total foam volume (V_f) at a specified temperature and pressure.[5]

$$f_{rTP} = \frac{Vg}{V_f}$$

f_{rTP} = Foam quality, dimensionless
Vg = Volume gas phase, cubic feet
V_f = Total foam volume, cubic feet

In one hydrocarbon fracturing treatment, the recommended foam fracturing treatment allowed for a liquid rate of 3 BPM and a gas rate of 7 BPM, with a total rate of 10 BPM. Proppant carrying foam quality was 66 to 70 with a straight nitrogen flush. Proppant in the liquid phase was 11.6 lbs per gallon, giving a bottom hole concentration of 3.48 lbs per gallon. Flowback after 1 1/2 hours shut-in time gave a return of 95 percent of the fracturing fluids in 24 hours. See Table 1 for field results.

TABLE 1—FOAMED HYDROCARBON FRACTURING RESULT

BEFORE TREATMENT				ONE WEEK			30 DAYS		
WELL NO.	BOPD	BWPD	MCF GAS/DAY	BOPD	BWPD	MCF GAS/DAY	BOPD	BWPD	MCF GAS/DAY
1	New Well			105	0	130	70	—	100
2	New Well			5	95	0	5	95	0
3	Well Shut In for 1 year			0	0	70	0	0	70

Using 70-quality foamed aromatic hydrocarbons has proven useful in cleaning the wellbore and the immediate formation region where heavy hydrocarbons such as paraffin have restricted water injection. The foaming of the aromatic (xylene) allows excellent penetration of the formation, and with the solvent properties of the xylene phase the paraffin can easily be put in solution. Paraffin and residual oil can be removed a greater distance from the wellbore using this technique because of the efficiency of foam. The foam was allowed to remain on the formation and in the wellbore for 1 hour of shut-in time, and then flowed back.

Using aromatics for the purpose of removing paraffin is not a new treatment. Foaming these aromatics incorporates the benefits of the solvent with the excellent efficiency of foam. Foam has considerable carrying capacity and thus may remove particulate material in the formation, such as formation fines and debris from previous stimulation.[8] Late evaluation of flowback fluids shows suspension of solids in fluid. Because of these properties, additional silts and clays that have been trapped by the paraffin are carried out of the formation to the surface by the foam. These suspended silts are removed to prevent restriction of flow and possible plugging of the formation. Removal of the suspended silts also prevents future contamination of the formation during subsequent acidizing or fracturing treatments. The paraffin is removed in solution together with the silts, leaving the formation, in most cases, with improved permeability.

The foamed aromatic treatments after clean-up are usually followed by acid or low-quality foamed acid treatments as previously described by Holcomb and Wilson. Results were better when acid or foamed acid was preceded by foamed xylene. The results of returned solids in the foamed xylene are in Table 2.

TABLE 2 SOLIDS RETURNED IN FLOWBACK OF FOAMED AROMATIC CLEAN-UP FLUIDS IN INJECTION WELLS.

WELL NO.	% PARAFFIN	% SILTS	TOTAL % SOLIDS
1	37.5%	62.5%	6.2%
2	41.0%	59.0%	5.7%
3	35.4%	64.6%	3.1%
4	33.0%	67.0%	2.9%
5	30.5%	68.5%	3.0%
6	41.0%	59.0%	5.3%
7	15.8%	84.2%	3.0%

Total Solids recorded as percent by volume of samples taken during flowback.
Percent paraffin and percent silts reported as percent in Total Solids.

The use of a foaming agent to remove liquid buildup has become a major method to remedy liquid loading in wells producing below the critical gas rate.[4]

The test runs documented by Libson and Henry were run where the liquid load was formation water. Tests have been run with great success where condensate loading has restricted gas flow. A hydrocarbon foaming agent was injected in the casing-tubing annulus with a chemical pump, and production recovery was timed. By creating foam, hydrostatic head is reduced, and the liquid is recovered, and it continues to unload in a foamed state. The gas phase of this foam is natural gas, which is the major product of these wells. Because of the synergistic blend of two oil-soluble surfactants, one fluorocarbon and one hydrocarbon, the surface tension of the hydrocarbon (condensate) can be lowered to 22-25 dynes/cm. The foaming and recovery of these fluids is an immediate process after foamer addition, and non-production time is reduced to a minimum, as opposed to the previous technique of swabbing. The foam properties allow for a continuous extended unloading process at low concentrations of foaming agents, i.e. 0.2 percent.

FOAMING AGENT REQUIREMENTS

Holcomb and Blauer listed the following specifications for foaming agents to be used in foam fracturing.

1. Foaming agents used in foam fracturing must immediately produce a stable foam upon injection of gas.
2. The foaming agent must be chemically compatible with any type of liquid phase used for foam fracturing.
3. The foaming agent must not have such stability that it will not readily break when pressure is released and bubbles expand.
4. The foaming agent must be compatible with the formation and not cause irreparable permeability damage.
5. Concentrations of the foaming agent should be low to minimize problems of formation incompatibility mixing, and disposal of injection fluids.
6. Cost of foaming agent at required concentration must be reasonable.

For incorporation of foaming agents for hydrocarbons these specifications should be added:

7. The foaming agent should be a non-emulsion agent to ensure formation fluid compatibility.
8. The hydrocarbon foaming agent should exhibit stability to temperatures of 250° F.
9. The hydrocarbon foaming agent must be able to overcome losses of hydrocarbons to the mechanisms of imbibition or capillary pore blockage by surface tension reduction (i.e. 22-24 dynes/cm).

Foaming agents used in well clean-outs in fluids such as aromatic solvents should provide suspension properties which will enhance the suspension properties of the existing foam.

Tests of the half life of foams and the ability of a foam to exist under pressure (1500 psi) have indicated that hydrocarbon foamers which are a blend of fluorocarbon and hydrocarbon materials improve the chemical and physical properties of a foamed system. The mechanism for this improvement, as presented by Holcomb and Wilson, is the lowering of the contact angle or an improved wettability effect as well as the highly stable fluorocarbon chain. Additional benefits of fluorocarbon blends are low surface tension, increased foam stability, and thermal stability as a result of the stable fluorocarbon chain.[9]

Concentrations of the hydrocarbon foaming agent, depending on the type of treatment and the hydrocarbon being foamed, vary from 0.3 percent to 0.6 percent. Where liquid loading of wells is experienced, concentration as low as 0.05 percent should be all that is required to initiate unloading condensate in the foam of a foamed hydrocarbon.

FIELD RESULTS

In fracturing with foamed hydrocarbons, both foamed gelled condensate and foamed gelled kerosene have been used. Fracturing with a foam as documented by Holcomb and Blauer requires additional monitoring to ensure the foam quality, proppant dispersion, rate, and correct treating pressures. To accomplish the required proppant concentrations at bottom hole on well no. 1, concentrations at the blender required 11.6 lbs per gallon of proppant. Foam quality necessary for this foam fracture was computed to be between 65 and 70 quality.

The breakdown pad was 16 bbls of gelled kerosene. After the pad was on spot, the foam was initiated with the injection of nitrogen into the line. Proppant concentration was increased to 11.6 lbs per gallon. The flush was with nitrogen. The fluid rate was 3 BPM; the Nitrogen rate was 7 BPM (a 10 BMP total rate). A total of 10,000 gallons of gelled kerosene was pumped as well as 410,000 cu. ft. nitrogen. Shut-in time was 1 1/2 hours. After 1 1/2 hours, flow back was started. The first 24 hours of production yielded 105 BOPD and 130 MCF/day gas. After 30 days, the well is producing 70 BOPD and 100 MCF/day gas. Other treatments of the same formation, Crockett Sand, with gelled kerosene gave results of only 15-20 BOPD and no gas in the same field. One other well in this field has been treated with foamed hydrocarbon and it has been an average well for this area with 5 BOPD and 95 BWPD. The perforations were 98 feet lower in the formation on the second well.

The San Miguel formation was treated with foamed gelled condensate as the fracturing fluid. This treatment was smaller in volume, using 2653 gallons of produced condensate. The foam quality was computed to be 66 quality. A concentration of 6.67 lbs per gallon proppant was added at the blender, yielding 1 lbs per gallon at bottom hole. The results of this well, which had been shut-in for 1 year, gave 70 MCF per day gas. This was commercial since a low pressure production pipeline was available (see Table 1).

The use of foamed aromatics has proven to be very successful when followed by other completion treatments. The treatments on wells in this area with normal acid stimulation have produced some improvements. A 70 quality aromatic foam of 500 gallons xylene pumped before an acid treatment has greatly enhanced the final results. Although all the field production data is not available for publication at this time, the results have been judged excellent by the operator. Data on the composition of the returned solids is listed in Table 2, showing the percent paraffin and silts contained in the flowback. Field results indicate that the increase in injection after foamed acid treatments is substantial. When a 500- to 1000-gallon foamed xylene clean-up is performed before a 6000-gallon foamed 15 percent hydrochloric acid treatment, the increase in injection rate is larger and the injection pressure requirements are reduced. Further evaluation will be published when the data is available.

Hydrocarbon foamers to reduce surface tension and foam condensate to allow unloading of hydrostatic pressure build-up have been tested and have proven to be a more practical method than swabbing. Chemical application (as described in "Field Applications") is becoming a major method to control liquid loading and is under consideration in an extensive well-stimulation program because of the effectiveness of the pilot test. Figure 5 shows a 56 hour period with the unloading fluids in total volumes as produced from the well under study.

FIELD EQUIPMENT SET-UP FOR FOAM FRACTURING

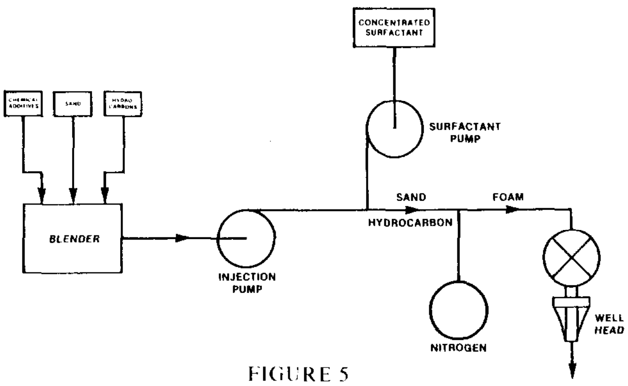


FIGURE 5

ECONOMIC COMPARISONS

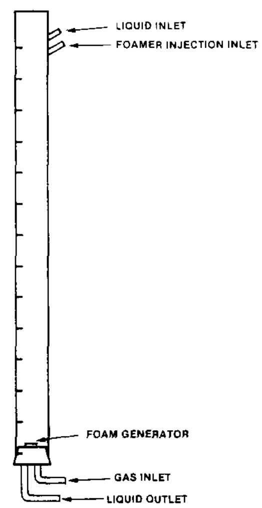
In stimulation with hydrocarbons at their current cost (kerosene averaging $0.55 per gallon and xylene averaging $0.91 per gallon), treatments consisting of foamed hydrocarbons are economically justified. Nitrogen costs are averaging $1.00/100 scf. Fluid costs for a 30,000 gallon fracturing treatment would average $16,500 for kerosene. Kerosene prices for the 70-quality foam would be $4950, and the nitrogen would cost $3860. The total cost of the fluids involved in this foam fracture example would be $8810. This is a savings of 46.6 percent on the cost of fluids. Cost of gelling and fluid loss chemicals must also be taken into consideration when using a gelled kerosene fracturing fluid. Transportation and pumping of the fluids at present costs are equivalent.

Foam flow-back can be started after a 1 hour shut-in time. The rate of flow-back is also quicker because of the gas phase and reduced hydrostatic head.[1] Fluid recovery is rapid and complete. Of the wells treated with foam fracturing fluids, 90 percent required no additional cleaning operations such as swabbing units. This percentage includes water-based foam treatments. The enhanced production allows for quicker pay out, and more rapid return to production, allowing better payout.

LAB EQUIPMENT AND RESULTS

Foam half-life analysis is used to test both the foamer and the type of liquid phase the foamer can best foam. A solution of the desired hydrocarbon and the volume of foamer to be tested were placed in a foam column. Figure 6 shows the type of apparatus used. The volume of fluid to be tested was a total of 1000 millileters. The foam was generated by introducing the gas phase, air, at the bottom of the fluid to be foamed. An air stone was used to disperse the gas phase in solution. The rate of the air was varied to obtain the "tightest" foam and then left constant for the following test.

FOAM COLUMN



APPARATUS USED IN HALF LIFE TESTS.
FIGURE 6

Generation of the foam was started. It was continued until all fluid was foamed. The gas was discontinued and an initial foam height reading was taken. The second reading was taken when one half of the foam had broken and the time was recorded as the half life of the foam. Concentration of foamer was varied for each hydrocarbon fluid tested (Table 3). The results were interpreted as a comparison of foamer quantities and its ability to foam various hydrocarbons.

Foams were also tested for stability under pressure with the apparatus shown in Figure 7. Pressures of up to 1500 psi were used to test various quality foamed kerosenes. The foam proved to be stable under pressure with 52 to 90 quality foam.

TABLE 3 FOAM HALF LIFE WITH VARIED CONCENTRATIONS OF FOAMER IN VARIOUS HYDROCARBONS.

HYDROCARBON	% BY VOLUME CONCENTRATION OF FOAMER	HALF LIFE (minutes)
Kerosene	0.1%	3.0
	0.2%	3.2
	0.3%	4.6
	0.4%	4.7
	0.5%	7.2
Xylene	0.1%	1.1
	0.2%	5.0
	0.3%	8.4
	0.4%	17.8
	0.5%	19.3
Diesel	0.1%	4.5
	0.2%	5.0
	0.3%	6.2
	0.4%	7.3
	0.5%	7.0
San Andres Crude Oil	0.1%	7.3
	0.2%	7.8
	0.3%	10.4
	0.4%	14.8
	0.5%	16.9
Condensate	0.1%	6.2
	0.2%	8.3
	0.3%	8.9
	0.4%	9.4
	0.5%	9.7

FOAM GENERATOR UNIT

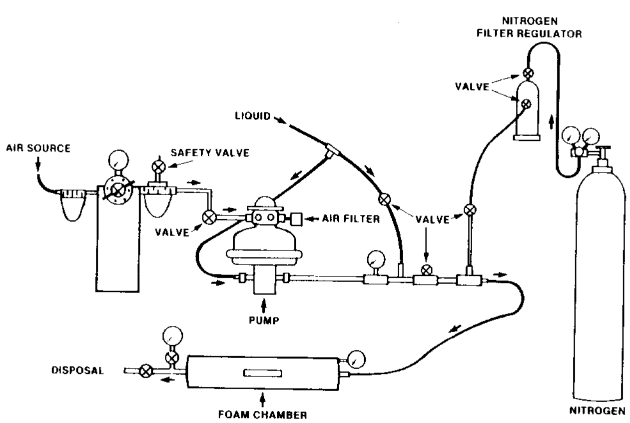


FIGURE 7

Fluorochemical surfactants as tested by Clark,[10] show the ability to depress the surface tension of non-polar organic liquids (Table 4). The surface tension values were determined by the use of a duNouy tensiometer. The fluorochemical surfactants are listed as FC-A, B, and C. The test were run at concentrations of 0.2 percent active surfactant in heptane and toluene. Active surfactant (0.1 percent) was added to kerosene and crude oil. The surfactant in all cases lowered the surface tension. The fluorochemical surfactants are some what less effective on heptane as the data shows.

CONCLUSIONS

1. Foamed hydrocarbons have been used to successfully fracture treat condensate and gas wells with good initial success. Media foamed include kerosene and San Miguel condensate.
2. A foamer has been developed to form hydrocarbons, which is a synergistic blend of hydrocarbon and fluorocarbon-based surfactants which are oil soluble.
3. A foamer has been developed and tested which will produce a stable foam in the fracturing qualities of 52 to 90.
4. A foamer has been developed and tested which will lower hydrocarbon surface tensions to less than 25 dynes per centimeter, and subsequently prevent emulsions with reservoir water and oil systems, and produce tight foams (bubble sizes in the 20-50 micron range).
5. A system whereby xylene is foamed and pumped into injection wells converted from old producers has been used and shown to remove residual oil and paraffin build-up so as to allow more efficient acidizing and subsequently lead to longer lasting lower pressures and higher water injection rates.
6. A foaming agent system has been developed where a synergistic hydrocarbon/fluorocarbon foamer is used via chemical injection with a water foamer in the unloading of condensate/water hydrostatic build-up in low pressure, low productivity gas wells.
7. Successful field tests have shown the utility of foaming aromatic kerosene and condensates for greater stimulation and treating effectiveness and efficiency.
8. Economically the cost of fluids can be reduced by foaming. The dilution of hydrocarbons with nitrogen in the form of foam allows improved stimulation with reduced cost.

9. Laboratory tests have been shown which indicate the utility of a synergistic hydrocarbon/fluorocarbon surfactant in effectively foaming several types of hydrocarbon media in a variety of oilfield conditions.

TABLE 4 SURFACE TENSION DEPRESSION IN ORGANIC LIQUIDS BY FLUOROCHEMICAL SURFACTANTS.

Surface Tension in mN/m at 22° C.

SURFACTANT	0.2% in Heptane	0.2% in Toluene	0.1% in Kerosene	0.1% in Crude Oil
-0-	20.5	29.0	28.5	26.5
FC-A	20.0	25.5	20.5	20.5
FC-B	–	20.0	22.5	20.5
FC-C	19.5	22.0	24.0	24.0

SUMMARY

Foaming hydrocarbons can be utilized in a variety of stimulation techniques including fracturing, paraffin and residual oil removal, and fluid hydrostatic unloading. The development of a synergistic fluorocarbon/hydrocarbon foam has allowed these hydrocarbons to be effectively foamed while taking the compatibility of formation and formation fluids. With this new foamer and foamed stimulation technique, successful field applications have been gained in the areas of fracturing, paraffin and residual oil clean-up, and condensate unloading.

The uses of hydrocarbon foamers have been well explored. The advantages of these uses are both economical and efficient. Incorporating the hydrocarbon foamer with conventional hydrocarbon treating fluids produces a method by which the desirable properties of foams and hydrocarbons can be combined.

REFERENCES

1. Blauer, R. E., and Kohlaas, C. A.: "Formation Fracturing with Foam," paper SPE 5003 presented at the 49th Annual Fall Meeting of the Society of Petroleum Engineers, Houston (October 6-9, 1974).
2. Holcomb, D. L., and Wilson, S. C.: "Foamed Acidizing and Selective Diverting Using Stable Foam for Improved Stimulation," Proc 25th Annual Southwestern Petroleum Short Course, Lubbock (April 20-21, 1978).
3. Rohret, Matthew, T., and Jones, T. C.: "Stimulation of the Neabrara Formation Using Foamed Methanol-Water," paper SPE 7174 presented at the 1978 Rocky Mountain Regional Meeting of the Society of Petroleum Engineering of AIME, Cody, Wyoming (May 17-19, 1978).
4. Libson, Tim N., and Henry, James R.: "Case Histories: Identification of and Remedial Action for Liquid Loading in Gas Wells-Intermediate Shelf Gas Play," paper SPE 7467 presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston (October 1-3, 1978).
5. Holcomb, D. L., and Blauer, R. E.: "Foam Fracturing Shows Success in Gas, Oil Formation," presented at the 22nd Annual Southwestern Petroleum Short Course, Lubbock (April 6, 1975).
6. Mitchell, B. J.: "Viscosity of Foam," PhD thesis, University of Oklahoma, 1969.
7. Blauer, R. E., and Mitchell, B. J., and Kohlaas, C. A.: "Determination of Laminar, Turbulent and Transitional Foam Flow Friction Losses in Pipes," SPE 4885 presented at SPE-AIME 44th Annual California Regional Meeting, San Francisco (April 4-5, 1974).
8. Wilson, Stephen C.: "Foamed Acid Stimulation of the San Andres: An Area Study," *Petroleum Engineer International* (May 1978).
9. Holcomb, D. L.: "Fluorochemical Surfactants; Their Current and Future Applications in Oil and Gas Well Stimulation," presented at the 24th Annual Southwestern Petroleum Short Course, Lubbock (April 21-22, 1977).
10. Clark, Henry B., Pike, Myron T., Rengel, Gayle L.: "The Use of Fluorochemical Surfactants in Non-Qqueous Stimulation Fluids," presented 1979 SPE of AIME International Symposium on Oilfield and Geothermal Chemistry, Houston (January 22-24, 1979).

ACKNOWLEDGMENTS

The authors wish to thank Cardinal Chemical, Inc. for permission to print this paper. Also the authors would like to thank 3M Company for their cooperation in this project. They also wish to express their appreciation to Jacque Thompson for typing the manuscript.